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# DISCRETE WAVELET TRANSFORM BASED MULTISPECTRAL FILTER ARRAY DEMOSAICKING

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## ABSTRACT

The idea of colour filter array may be adapted to multispectral image acquisition by integrating more filter types into the array, and developing associated demosaicking algorithms. Several methods employing discrete wavelet transform (DWT) have been proposed for CFA demosaicking. In this work, we put forward an extended use of DWT for multispectral filter array demosaicking. The extension seemed straightforward, however we observed striking results. This work contributes to better understanding of the issue by demonstrating that spectral correlation and spatial resolution of the images exerts a crucial influence on the performance of DWT based demosaicking.

**Index Terms**— Multispectral, imaging, filter array, demosaicking, discrete wavelet transform

## 1. INTRODUCTION

Man-made image sensors permit the conversion of an optical image to its electronic representation. Nonetheless, they are incapable of distinguishing the incident irradiance at one wavelength from another since all that matters is the number of photons. However, what precisely produces the sensation of colour is the form that the spectral power distribution of radiation takes. Therefore single-sensor based electronic trichromatic imaging systems mostly employ an array of colour filters in order to sense a portion of the spectra selectively on a pixel-by-pixel basis, which permits the acquisition of a colour image by means of a single sensor at one exposure, at the cost of reduced spatial sampling rate. A companion post-processing step, called demosaicking, becomes essential to estimate the lost information thus recovering colour images of full resolution. An example of such a colour filter array (CFA) that has achieved commercially notable success is known as Bayer filter mosaic [1], named after its inventor, Bryce E. Bayer. A Bayer-like filter array meant for colour image acquisition normally consists of three types of filters,

i.e., red, blue and green, as shown by the leftmost pattern in Figure 1(a). Since one CFA is typically customised for a specific sensor design, each pixel on the sensor corresponds to a filter tile of one particular type. In other words, parts of the incoming spectra pass through the filters and strike the sensor, whereas other parts are either absorbed or reflected by the filter and thus lost. Nonetheless, thanks to the spatial and spectral inter-pixel correlation an image may possess, the lost information about the spectra can be estimated through demosaicking, an operation in the image processing chain carried out on the mosaicked image read from the sensor. Consequently each pixel will comprise three components, thereby resulting in a full colour image.

A large number of CFA demosaicking algorithms have been proposed over the decades [2]. In general, these methods can be divided into two main categories according to whether the inter-channel correlation is utilised. The former includes the techniques such as nearest-neighbour, bilinear and bicubic [3] interpolation and more complicated methods take edges into account in order to avoid cross-edge interpolation [4]. Methods falling into this category estimate unknown colour components by exploiting the spatial correlation between sampled colours in a certain spectral plane, and function plane by plane. Algorithms of the other group bring the inter-channel correlation into play in a number of ways. For instance, some interpolate the difference between one colour plane and another [5] or the ratios of one colour plane to another [6], and some utilise the inter-channel differently by observing and filtering the spectra in frequency domain [7, 8]. In addition, discrete wavelet transform (DWT) also stimulates particular research interest, since it transforms an image into various frequency bands, and natural images often possess rather similar high-frequency information among these bands, which provides yet another solution to demosaicking problem.

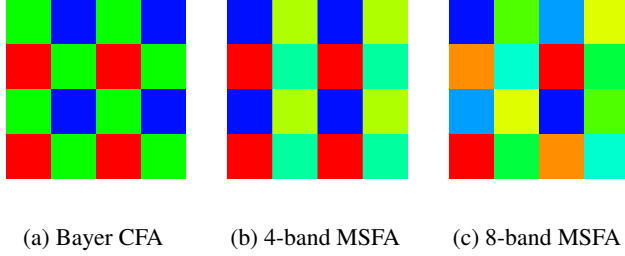
The idea of capturing a colour image by means of a CFA fits itself for the multispectral image acquisition as well. In recent years, sustained research effort went into designing multispectral filter array (MSFA) and developing associated demosaicking algorithms. The first notable work in this regard was conducted by Miao *et al.* [9] who develop a generic binary tree based generation method of MSFA spatial ar-

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**Fig. 1:** Examples of CFA and MSFA design.

range starting from a checkerboard pattern, and further proposed a generic MSFA demosaicking method following the same binary tree structure [10]. Baone and Qi [11] treat the MSFA demosaicking problem as an image restoration problem, and another interpolation algorithm introduced by Brauers and Aach [12] low-pass filters colour channel differences. Monno *et al.* [13] propose a novel multispectral demosaicking algorithm by extending existing upsampling algorithms and further interpolate each spectral component with guided filters capable of preserving structures [14]. As an example of adapting CFA demosaicking algorithms to MSFA demosaicking, Wang *et al.* [15] investigate median filtering operation in MSFA demosaicking and post-processing with the aim of alleviating colour artefacts. The intrinsic similarity between colour and multispectral images in terms of inter-band spectral correlation makes the utilisation of DWT potentially beneficial to MSFA demosaicking.

In this work, we first present a demosaicking algorithm making use of DWT. It begins by a review of related work in Section 2. A description of the proposed method is explained in Section 3. An introduction of the experiments and the results are shown in Section 4. However, we observed unexpected results and subsequently performed brief analyses on the results in Section 5 which leads to reasonable conclusions drawn in Section 6.

## 2. CFA DEMOSAICKING BASED ON DWT

In recent years, DWT is referred to and taken advantage of by a succession of research work on CFA demosaicking. As known, DWT makes use of subband coding in which an image is decomposed into a set of bandlimited components. A commonly seen four-band decomposition splits an image into four quadrants containing an approximation subband, a horizontal detail subband, a diagonal detail subband, and a vertical detail subband, respectively. All subbands, except of the approximation subband, represent high frequency information at a certain scale. It is the subband coding that builds a viable foundations for DWT based demosaicking by taking into account the inter-channel correlation most images bear.

To the best of our knowledge, Gunturk *et al.* [16] first bring the DWT in CFA demosaicking. The algorithm begins

by an initial estimation of all channels by means of intra-channel interpolation. It then decomposes the channels with a filter bank into four sub-bands and the high-frequency sub-bands of the red and blue channels are updated according to some criteria. Next, the ground truth red/blue samples are inserted back to the reconstructed channels. The last two steps are repeated until a stopping criterion is satisfied. The initial estimates of the green samples follow the same procedure as red/blue samples do.

Driesen and Scheunders [17] propose a similar approach. However the initial interpolation is performed on the luminance image derived from the original RGB channels, as the interpolated luminance image possess higher spatial resolution than interpolated R/G/B channels. Then both the luminance image and the original RGB channels are discrete wavelet transformed resulting in wavelet coefficients. Two merging rules are applied singly in order to benefit from the inter-channel correlation. One of them, named “replace” rule, simply replaces at each scale the coefficients of each band of R/G/B band images with the corresponding coefficients in the luminance image, whereas the other, labelled “max” rule, compares the coefficients of each R/G/B band with those of the luminance image, and assigns the larger one to each R/G/B band. The demosaicking is accomplished when the updated wavelet coefficients are inversely transformed.

Chen *et al.* [18] introduce the concept of downsampled (DS) images. First, this method is initiated by an estimation of missing green pixels with edge-directed interpolation and missing red/blue pixels with bilinear interpolation, from which the DS images are then derived and wavelet transformed. Next, the “replace” rule is applied to the high-frequency sub-bands. The last step aims to reduce colour artefacts by median filtering the low-frequency wavelet sub-bands and updating high-frequency sub-bands of Red/Blue images with those of the Green images. A simplified version of such an idea was implemented by Courroux *et al.* [19].

Jeong *et al.* [20] also use the polyphase-like downsampling prior to DWT. The wavelet coefficients of the low frequency sub-bands are then estimated by means of an edge adaptive interpolation method using high frequency wavelet coefficients as the edge indicators. An estimation of the coefficients of the high frequency sub-bands is performed in accordance with the “replace” rule.

Slightly different from the above approaches, Kim *et al.* [21] perform DWT on observed DS images to obtain the missing high-frequency sub-bands by linear estimation, and estimate the low-frequency sub-bands by wavelet transforming the DS images that have been interpolated beforehand.

Indicated by the aforementioned literature, DWT based demosaicking methods outperform the conventional counterparts relying merely on intra-channel correlation.

### 3. MSFA DEMOSAICKING BASED ON DWT

As mentioned above, DWT decompose images into a series of sub-bands with different frequency components. The spectral correlation, namely the inter-plane similarities, then comes into play. In theory, the idea is also applicable to multispectral images. Inspired by this, we extend the application of DWT into MSFA demosaicking.

The essence of the proposed method may be encapsulated by the concept of DS images, the Haar wavelet (D2), the “replace” rule for the estimation of high-frequency sub-bands and bilinear interpolation for the estimation of low-frequency sub-bands. The workflow is summarised as follows.

1. Estimate high-frequency coefficients.
  - (a) Construct DS image using polyphase transform.
  - (b) Apply discrete wavelet transform.
  - (c) Estimate the coefficients of the missing DS images at high-frequency sub-bands according to the “replace” rule.
2. Estimate the low-frequency coefficients.
  - (a) Apply bilinear interpolation to the mosaicked image plane by plane.
  - (b) Construct DS image using polyphase transform.
  - (c) Apply discrete wavelet transform.
  - (d) Replace the coefficients of the missing DS images at low-frequency sub-bands with those of the interpolated DS images.
3. Recombine the low-frequency and high-frequency components and apply inverse discrete wavelet transform.
4. Reconstruct the demosaicked image of full resolution.

This method is compatible with any MSFAs with regular mosaic patterns regardless of number of channels. For the purpose of evaluation and comparison, we apply this method to a set of RGB images in addition to multispectral images.

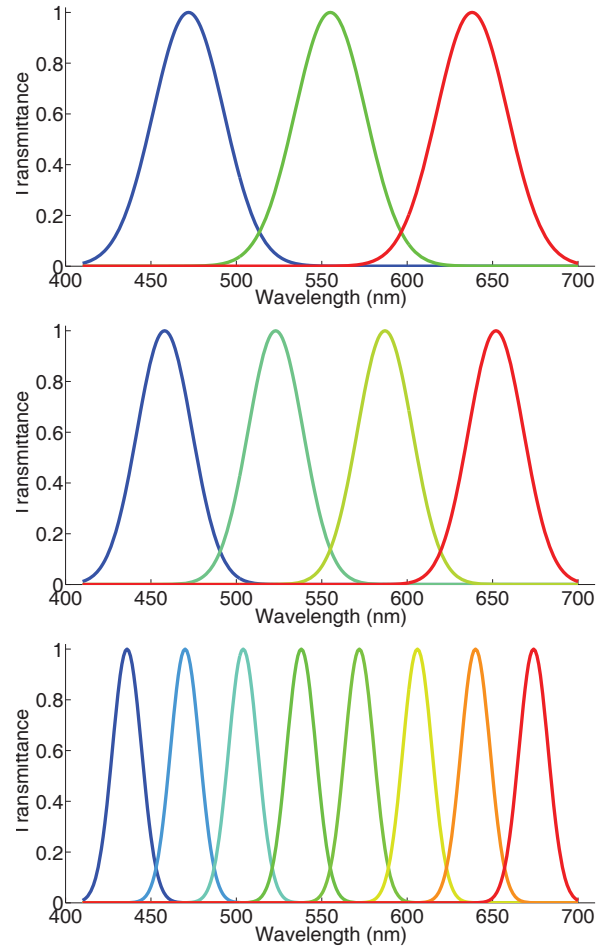
### 4. EXPERIMENTS AND RESULTS

Two hyperspectral image database were used in this study. 12 hyperspectral reflectance images are from Foster *et al.* [22]. The test set consists of a mixture of rural scenes containing rocks, trees, leaves, grass, and earth and urban scenes. The spectral span ranges over 400-720 nm in 10 nm steps yielding 33 bands, while scene 5 has only 32 bands due to the noisy 720 nm band. Another 32 hyperspectral images are from the CAVE project [23]. Divided into 5 sections, the images are of a wide variety of real-world materials and objects, covering various colourful stuffs, skin, hair, paints, food, drinks and

fake stuffs mimicking the colour of real objects mentioned. The spectral span ranges over 400-700 nm in 10 nm steps yielding 31 bands. For the ease of processing and comparison, the spectral range between 410 nm and 700 nm was used in this study resulting in 44 hyperspectral images of 30 bands. A framework that simulates the key elements of an imaging system was built as a testbed.

Also employed are 24 Kodak RGB test images [24] for the sake of evaluation of the proposed methods. These images are widely used in the realm of image related research, and are utilised to evaluate the performance of algorithms in the majority of aforementioned papers about DWT based CFA demosaicking.

In addition, one artificial pattern that includes one circle and one line and resembles the first publicly broadcast test card, was also created and employed as a test image. It has 30 bands as well, but only two reflectance values, namely, 0 and 1.



**Fig. 2:** Filter design for 3-band, 4-band and 8-band set-up.

To conduct the test, two steps were followed. In case of hyperspectral image sets, we decided on a set of algorithms and parameters, as described below.

1. Images were rendered with the illuminant of CIE D65;
2. In each case, spectral transmittances were determined so that each of them had a regular Gaussian shape and the centres of them were evenly distributed over the pertinent spectrum with the distance of  $2 \times \sigma$ , as shown in Figure 2;
3. Three filter array patterns were chosen, Bayer type 3-band setup, 4-band setup in form of  $2 \times 2$  moxel<sup>1</sup> and 8-band in form of  $4 \times 4$  moxel, the moxels were repeated across the whole image;
4. The filter arrays were designed in accordance with the binary tree approach proposed by Miao *et al.* [9], a perfect binary tree to be exact, with two levels and three levels corresponding to 4-band and 8-band arrangements respectively, as indicated in Figure 1;
5. Two additional demosaicking algorithms, bilinear interpolation and Miao *et al.*'s binary tree based progressive demosaicking [10], were implemented and compared with the proposed method;
6. To visualise the images, the original hyperspectral images were rendered in the sRGB colour space, and the demosaicked multispectral images were first restored to hyperspectral images with a spectrum reconstruction method exploiting a priori knowledge of the imaged objects [25] and then rendered to sRGB.
7. Evaluation of the performance was carried out by means of peak signal-to-noise ratio (PSNR) computed between the original and reproduced multispectral images, so as to avoid the error introduced by the spectrum reconstruction.

In case of Kodak images, we follow step 5 & 7 described above.

Results for Kodak and hyperspectral images are shown in Figure 3-6 respectively. As can be seen, the proposed method outperforms two other algorithms for most Kodak RGB images. Surprisingly and interestingly, the order of performance is almost inverted in case of hyperspectral images regardless of the number of channels.

## 5. DISCUSSION

Indicated by the results is a seemingly obscure issue. Nevertheless, further analyses of the cross-correlation between high frequency sub-bands of the DS images partly uncover the mystery. As shown by Figure 7, Kodak images represented in yellow circles possess relatively higher correlation

<sup>1</sup>The smallest pattern repeated to form the MSFA. [15]

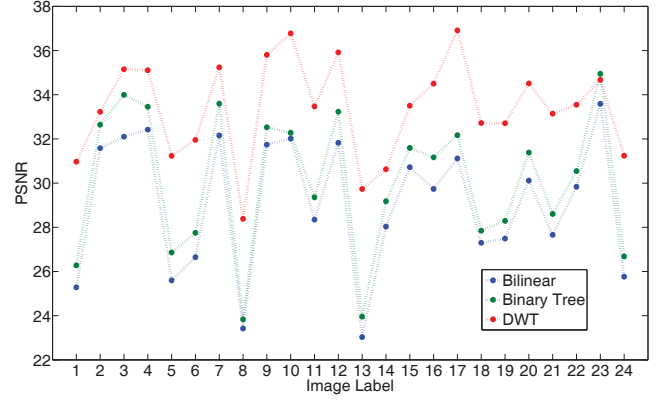


Fig. 3: Comparison of performance on Kodak images

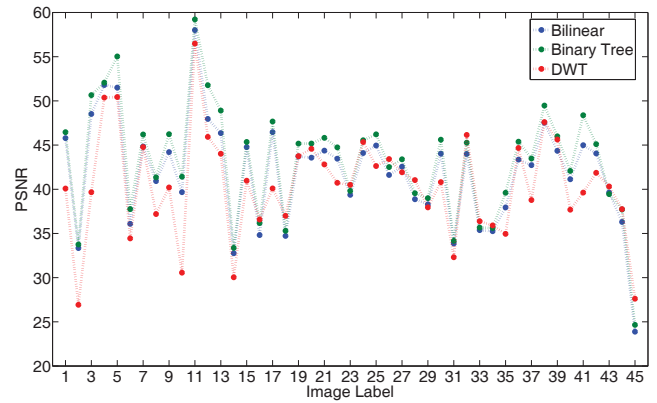
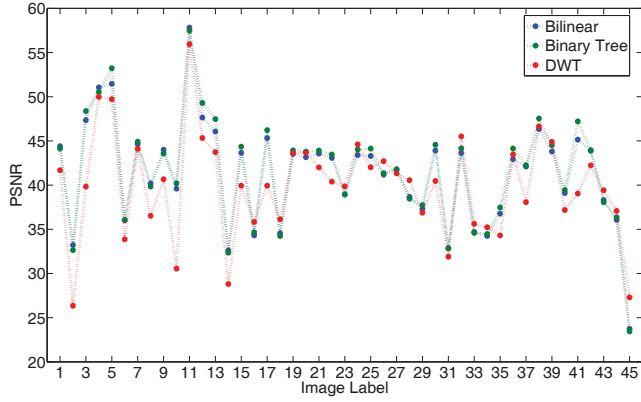


Fig. 4: Comparison of performance on 3-band multispectral images

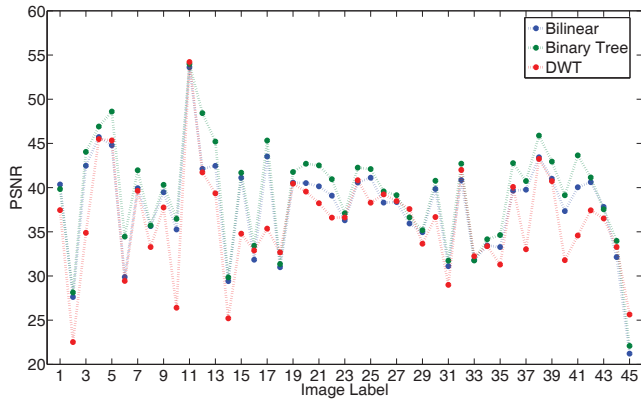
than the multispectral images plotted in red/green/blue. Further, PSNR difference between the proposed method and bilinear interpolation bears a somewhat linear relationship with the cross-correlation between the DS images. That is to say, the higher the correlation of the images is, the more we may gain from the proposed DWT demosaicking approach. It is consistent with the basic assumption and principles of the method.

Obviously the spectral correlation of a multispectral image depends not only on the original scene and the illumination, but also on the design of filters present on the CFA/MSFA. Tests performed have shown that the correlation increases when degree of overlap between adjacent filters increases. In addition, Kodak images were originally acquired by film cameras and scanned, whereas the hyperspectral images employed in our study were captured by digital cameras and filtered with idealised Gaussian-shaped filters. The discrepancy between the two systems might influence the correlation in a way.

Also notable is the fact that most of the images from the Foster set appear blurred to some extent in comparison with



**Fig. 5:** Comparison of performance on 4-band multispectral images

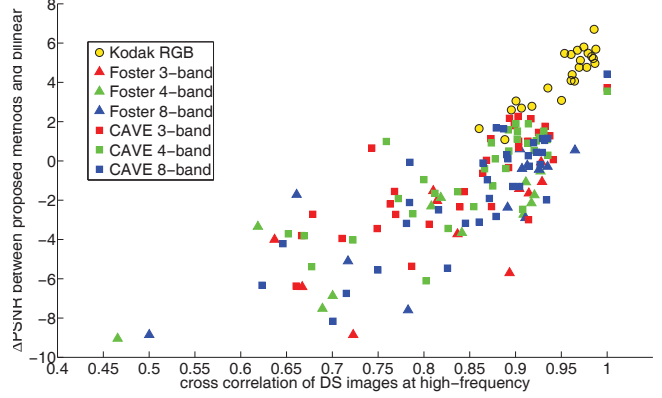


**Fig. 6:** Comparison of performance on 8-band multispectral images

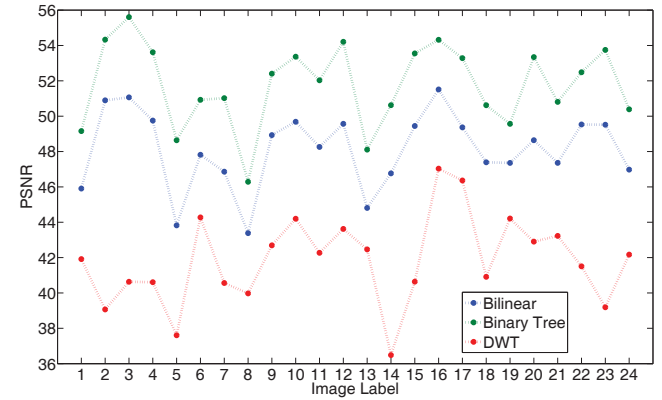
the CAVE set and Kodak images. This might be pertinent to chromatic aberration or vibration in the course of acquisition, and this also influences the spectral correlation. To verify the hypothesis, we blurred Kodak images by means of the convolution of each plane of an image and a Gaussian kernel and applied the same algorithms as in the previous experiment. Figure 8 illustrates the case when the kernel measures  $5 \times 5$  pixels with  $\sigma$  of 3. Clearly the DWT based algorithm turns the worst in contrast to the other two, contrary to the situation shown in Figure 3, which again illustrates the dependence of DWT demosaicking on the intrinsic properties of images.

## 6. CONCLUSION

In this work, we first propose to adapt DWT based MSFA demosaicking algorithms to multispectral demosaicking. They work quite well with the Kodak test image set, however an extension of such a method does not perform satisfactorily with the hyperspectral image set employed in the study. Experiments and analyses indicate that the spectral cross-correlation



**Fig. 7:** Difference of PSNR between proposed method and bilinear interpolation



**Fig. 8:** Comparison of performance on blurred Kodak images

plays an important role in determining the performance of the proposed algorithm. In other words, the “replace” rule depends largely on the assumption that the images are highly correlated, which explains the unexpected results. More in-depth and theoretical analyses are expected in order to evaluate the appropriateness of the use of DWT transform in multispectral demosaicking.

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